Examination of the DSN X-Band Weather Specifications

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Effects of weather on DSN system performance at X-band are examined by comparing a record of 64-meter system noise temperatures with weather observations taken at approximately the same times and places.

I. Introduction

As part of the specification of itself to the user, the Deep Space Network provides a probabilistic description of the weather-induced increases in signal attenuation and system noise temperature (SNT) at X-band. The description takes the form of a set of tables of X-band zenith cloud attenuation vs cumulative probability; the tables reside in Module TCI-40 (DSN Telecommunications Interfaces, Atmospheric and Environmental Effects) of Document 810-5; Rev. D (Ref. 1). In this article, they will be called the "810-5 tables."

The Voyager Project, whose planetary encounters could be affected seriously by weather, requested the DSN to reexamine the 810-5 tables in the light of two recent sources of information. The first source is a record of X-band zenith system noise temperatures measured from March 1976 to March 1977 at the three 64-meter antenna stations during precalibration and postcalibration of Viking tracks. We shall use the name "76-77 SNT data" or simply "SNT data" to refer to this data set. The second source is the result of a contract executed by Meteorology Research, Inc. (MRI), the same firm that provided the data for the 810-5 tables. MRI was given only the measurement times of the 76-77 SNT data, not the actual SNT values. They returned a data set containing their estimates of weather and X-band zenith cloud attenuation at those times. We shall use the name "76-77 weather data" or simply "weather data" to refer to this data set. Since cloud attenuation can be converted to added noise temperature, one can compare the 76-77 weather data to fluctuations in the 76-77 SNT data. The idea is to increase confidence in the 810-5 tables by checking the 76-77 SNT and weather data against each other. This assumes that the 810-5 tables arose from the same kind of weather data collection and processing as the 76-77 weather data. Unfortunately, this proviso could never be satisfied fully because the 810-5 tables are based largely on climatic summaries, not daily weather observations.

We shall present a comparison of the 810-5 tables, the 76-77 SNT data, and the 76-77 weather data. It will be seen that when the SNT and weather data are compared point by point, the correlation is low. The cumulative distributions agree better. On the other hand, the 810-5 tables look quite different from either the 76-77 SNT or the weather data.

II. Description of Data Sets

A. 810-5 Tables

The present edition (the second) of these tables is based on two reports by MRI. The first report, published in 1970 (Ref. 2), contains a set of cumulative distribution functions (cdf) of X-band (and S-band) zenith cloud attenuation. There is a distribution for each choice of DSN site (Goldstone, Canberra, Madrid), season (December-February, March-May, June-August, September-November), and day quarter (centered at 0000, 0600, 1200, and 1800 local time), except that no 0000 distributions for Canberra were given.

The Goldstone distributions are based on a year of cloud observations at Daggett, California; a summary of the data was compared to long-term averages at Edwards Air Force Base to make sure that the single year of record at Daggett was not abnormal. For Canberra and Madrid, it was necessary to rely on long-term statistics of cloud cover by seasons because daily cloud data were not available.

The distributions account for nonprecipitating clouds only. Unfortunately, the random variable whose distributions MRI provided is not cloud attenuation, but maximum cloud attenuation times the fraction of the sky covered. This quantity can roughly be considered as the time average of attenuation over a period long enough for many clouds to pass by the antenna.

MRI estimated that the attenuation values (given in dB) "should be correct within a factor of 10–20 on a statistical basis." Needless to say, these huge error estimates destroyed the credibility of the results. In 1976, MRI published a second report (Ref. 3), which outlined a procedure for modifying the 1970 distributions and put somewhat narrower multiplicative error bounds on the results. The modification concerns the possibility that some of the clouds that previously were treated as ice might actually have been liquid water clouds, which have much greater attenuation. This modification tends to push the distribution toward higher attenuations.

The JPL Telecommunications Division carried out the procedure of the 1976 report; the resulting distributions have been used by the Voyager Project for planning their encounter sequences. Independently, the author executed his own interpretation of the procedure. The multiplicative error bounds were folded into the distributions in such a way that they do not appear in the final result, which is a set of distributions with no error bounds. These distributions, which constitute the 810-5 tables, are essentially a smoothed version of those produced by the Telecommunications Division.

We remark here that the 0000 Canberra distributions simply duplicate those of 0600; we shall not attempt to defend this arbitrary choice.

B. 76-77 SNT Data Set

This record of 64-meter zenith X-band system noise temperature measurements is shown in Fig. 1. There are 273 data for DSS 14 (Goldstone), 324 data for DSS 43 (Canberra), and 284 data for DSS 63 (Madrid). System noise temperatures were measured by the Y-factor method. Each measurement is accompanied by the precalibration or postcalibration time tag (GMT). The actual time of the measurement was estimated by

$$\begin{aligned}\text{measurement time} &= \text{time tag} - 1 \text{ hour} \quad \text{for precal}\\ &= \text{time tag} + \tfrac{1}{2} \text{ hour for postcal}\end{aligned}$$

These time estimates were converted to local standard time and given to MRI. Accompanying the data are occasional notes about equipment problems or bad weather. Those points are marked on Fig. 1. The *absence* of a note, however, does not imply the absence of problems with equipment or weather.

The portion of DSS 14 data between 76-162 (year-day of year) and 76-240 has a mean 4.8 Kelvin above the rest of the record. This must have been due to equipment problems, not weather. To rescue these data, they were lowered by 4.8 K during processing. (Two data then fell below 21 K; these were deleted.)

On 76-316, a new X-band traveling-wave maser was installed at DSS 43. (The note "maser orange" in Fig. 1(b) refers to the new maser, which was being burned in.) The SNT quieted down immediately. Accordingly, none of the data before 76-317 was used. This is unfortunate because there are many genuine bad-weather points in this period. The deletion left 107 data for processing. Nevertheless, all 324 measurement times were given to MRI.

C. 76-77 Weather Data Set

Items from this data set that were used for the present study are:

(1) Time tag; MRI gathered weather data for the nearest hour to the measurement time furnished them from the 76-77 SNT data set.

(2) Fraction of sky covered by clouds.

(3) Fraction of sky covered by optically opaque clouds.

(4) Physical temperature of low clouds, if any, else the temperature of midlevel clouds, if any.

(5) Estimated maximum zenith X-band cloud attenuation; the actual zenith attenuation would vary from zero to the maximum as clouds passed through the antenna beam. Clear-air (oxygen and water vapor) attenuation is not included; if there were no clouds or only high clouds, then zero attenuation was returned.

The author converted attenuation to added noise temperature by the formula

$$T = T_p\,(1 - 10^{-A/10}) \tag{1}$$

where T = added noise temperature (Kelvin), T_p = physical cloud temperature (Kelvin), and A = cloud attenuation (dB).

D. SNT_0 Data Set

This is a subset of the 76-77 SNT data set consisting of the SNT measurements at the times for which MRI reported zero cloud attenuation. The SNT_0 data show the weather-independent scatter in SNT measurements, provided that one may neglect variations in clear-air attenuation and rely on the indications of clear weather in the 76-77 weather data.

III. Comparison of the 76-77 SNT and Weather Data Sets

A. Point by Point

Figure 2 shows scatter plots of the 76-77 SNT data vs the corresponding added noise temperatures from the 76-77 weather data for the three 64-meter stations. We have plotted only the points for which MRI reported a positive cloud attenuation; on the right side of each plot we show the histogram of the remaining points, namely the SNT_0 data. (If those points had been plotted, they would be superimposed along the left edges of the plots.) Off-scale points are shown at the tops of the plots.

In an ideal situation, the points would cluster about a line of slope 1, that is, each increase in cloud noise would be matched by an increase in system noise temperature. For those points below the "regression cutoff" lines, a least-squares straight line was fitted and a correlation coefficient computed. The correlation is 0.37 for Goldstone, 0.35 for Canberra, and 0.17 for Madrid. Clearly, the regression lines cannot be taken seriously.

We see two causes for the weakness of the coupling between the two data sets. First, the SNT_0 data show that much of the scatter in the SNT data is caused by nonweather effects. Second, the SNT and weather data sets are separated, both in time and in space. The measurement times of corresponding data in the two sets could differ by as much as one hour, for the SNT time is only an estimate, and the weather time is given only to the nearest hour. We estimate the standard deviation of the time difference to be about 25 minutes. As for the spatial separation, the weather data for Goldstone are based on observations at Daggett, about 60 km from DSS 14. We do not know the situations at Canberra and Madrid.

If cloud attenuation varied slowly over time and space, these separations might not drastically decouple the data sets. Unfortunately, sky noise records from a dedicated X-band radiometer at Goldstone exhibit sharp, narrow peaks separated by quiet periods. An example can be seen in Fig. 1 of Ref. 4. Two of the peaks have widths less than two hours.

To sum up, an item from the 76-77 weather data is an estimate of the added noise when looking through the thickest part of a typical cloud found in the general vicinity of the station at about the same time as the SNT observation. One could not expect a high correlation between these data sets.

B. Distribution Function Comparison

Having observed that the 76-77 SNT and weather data sets are nearly orthogonal, we turn to the examination of their one-dimensional cumulative distribution functions (cdf). A first cut at a comparison is given in Fig. 3, which was displayed at a Voyager Telecommunication Review. The distributions of added noise from the 76-77 weather data start at zero Kelvin, whereas the SNT distributions start at above 20 Kelvin. Although a baseline system noise temperature of 25 ± 3 Kelvin is specified in Ref. 1, we do not want to assume an arbitrary baseline, preferring rather to let the data speak for themselves in this regard. Hence, we shifted the cdf's so that they coincide at their medians, the 50-percent points.

The 76-77 weather cdf curve is actually the cdf of added noise temperature times the fraction of the sky covered by clouds; this is the crude cloud cover adjustment used in Ref. 2.

Because the SNT data contain nonweather fluctuations, comparing them directly with the weather data is perhaps ill-advised. Nevertheless, we can make a few observations if we confine ourselves to the higher probability levels, above the bulk of the nonweather fluctuations of the SNT. For Goldstone, the agreement is good above the 90% level; for Canberra, the agreement is good through the 90% level, but at the 95% level one can see the tail of the SNT cdf leveling off. This reflects the thin scattering of high system noise temperatures, 40 K and above, visible in Figs. 1(b) and 2(b). Such temperatures (more than 15 K above baseline) are not seen in the weather data, but we remind the reader that the weather data do not include precipitation. For Madrid, the weather data are clearly pessimistic. Again, above 95%, the SNT data have a few extremely high system temperatures.

The second comparison method folds the SNT_0 distribution into the 76-77 weather distribution before comparison with the SNT distribution. Let X and Y be independent random variables having the distributions of the SNT_0 and weather data. Then X represents the zenith SNT measurements during clear weather, and Y the weather-induced increases in SNT. The distribution of $X + Y$ is the convolution of the SNT_0 and 76-77 weather distributions; it is reasonable to compare it with the distribution of the total 76-77 SNT data set.

A different method of accounting for cloud cover is used here. Suppose that the maximum cloud brightness temperature is 4.2 K and the opaque cloud cover fraction is 0.7. We shall crudely model the situation by supposing that 7 out of 10 narrow-beam zenith observations around this time would see a 4.2-K cloud temperature, and that 3 out of 10 would see only clear air or a thin cloud section. Thus, when binsorting this weather datum, we add 0.7 to the bin for 4.2 K, and 0.3 to the bin for zero Kelvin. The sum of the bin counts is still the total number of data, as with an ordinary binsort.

Figure 4 shows the cdf's for 76-77 SNT and SNT_0 + 76-77 weather. The third curve is the cdf of SNT_0 + 810-5; we shall treat this in Section IV. For Goldstone, the good agreement is to be expected because the nonweather variations dominate the weather-induced ones in this desert climate. At Canberra and Madrid, it can be seen that the SNT_0 + weather distributions are more pessimistic than the SNT distributions up to the 95% level for Canberra and the 97% level for Madrid. Beyond these levels, the tails of the SNT distributions are extended by the few system temperatures greater than 40 K.

IV. Comparison of 810-5 With the 76-77 SNT and Weather Data

Recall that the purpose of this study is to validate (or invalidate, as the case may be) the DSN cloud attenuation distributions in Document 810-5. These represent long-term average probability levels. To do this, we have compared the SNT and weather data sets of 1976-1977 to each other in order to make conclusions about MRI-derived statistics in general. On the other hand, although the 1976-1977 weather is not expected to resemble closely the overall long-term climate, it is inevitable that one should compare the 810-5 tables with the two recent data sets, especially since the 810-5 distributions for Canberra and Madrid are based largely on climatic summaries, while the recent 76-77 weather data come from daily observations.

Figure 5 compares the 810-5 tables with the cdf of the 76-77 weather data set. Since the SNT data play no role, the entire set of 324 weather data for Canberra was used. The second method of Section III-B was used to adjust the weather data for cloud cover. The measurement times of the weather data, being dependent on the vagaries of Viking passes, are far from uniformly distributed over the times of day and seasons of the year. As noted in Section II-A, for each DSN site there are 16 distributions in the 810-5 tables, one for each season and day quarter. To produce the 810-5 distribution of Fig. 5 for a given DSN site, the number of 76-77 SNT times that fall into each of the 16 categories was counted and an appropriate weighted average of the 16 distributions computed. To convert attenuation to added noise temperature, Eq. 1 with T_p = 260 K was used. (The 76-77 weather data set shows that typical cloud temperatures fall in the range 270–280 K, but 260 K was used because Ref. 1 specifies it.)

In order to show what total system temperature measurements would look like if weather-induced noise followed the 810-5 distributions, we show on each section of Fig. 4 a cdf obtained by convolving the SNT_0 distribution with a weighted average of 810-5 added noise distributions. (For Canberra, only the 107 times of the "good" SNT data were used to determine the weights.)

One can see in both Fig. 4 and Fig. 5 that the upper tails of the 810-5 distributions are much heavier than those of the recent MRI weather observations. They are also heavier than the tails of the SNT distributions, especially for Madrid, in spite of the inclusion of rain in the SNT data and its exclusion from the 810-5 distributions.

V. Conclusions

From the comparison between the distributions of 76-77 SNT and of SNT_0 + 76-77 weather in Fig. 4, we conclude that on the average the added noise temperatures given by MRI are slightly higher than the SNT data. For Goldstone, the difference is obscured by the scatter in the SNT and SNT_0 data. For Canberra and Madrid, the 76-77 weather cdf is 2.5 K and 3.5 K higher at the 90% level than the SNT cdf. Beyond 95%, though, the SNT distribution reflects the presence of a few system noise temperatures beyond 40 K; these cannot occur in the weather data because the latter do not account for precipitation. It appears that the method used by MRI to convert a weather and cloud observation to X-band attenuation is reasonably accurate.

If we had not looked directly at the 810-5 distributions, we would be tempted to conclude from the foregoing that they provide a slightly pessimistic estimate of the effect of weather on DSN communication. The striking differences between the 810-5 distributions and the recent MRI weather data raise doubts, however. How much of these differences is caused by possible atypical weather during March 1976 to March 1977 at the DSN sites, and how much is caused by poor estimates of cloud attenuation statistics from climatic summaries instead of from daily and hourly records? It is a general consensus that the upper tails of the 810-5 distributions are far too heavy, hence no matter how well the 76-77 SNT and weather data agreed, they could not validate 810-5. It is therefore strongly recommended that the DSN collect a long-term database of system noise temperatures together with simultaneous measurements of weather parameters and indicators of microwave configuration. A system for doing this is being implemented; it includes a noise-adding radiometer for accurate measurement of system temperature, the Meteorological Monitor Assembly for collecting ground weather parameters, and, later, a water-vapor radiometer for estimating the depth of liquid water in the antenna beam. As such a database accumulates over the years, statistics gleaned from it will be built into a more accurate set of specifications for the effect of weather on DSN communication.

References

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3. Carbone, R. E., and Smith, T. B., *Attenuation Due to Clouds at X-Band,* Meteorology Research, Inc., Altadena, California, February 16, 1976.
4. Greenhall, C. A., "Simulation of Time Series by Distorted Gaussian Processes," *Deep Space Network Progress Report* 42-37, pp. 146–151, Jet Propulsion Laboratory, Pasadena, California, February 15, 1977.

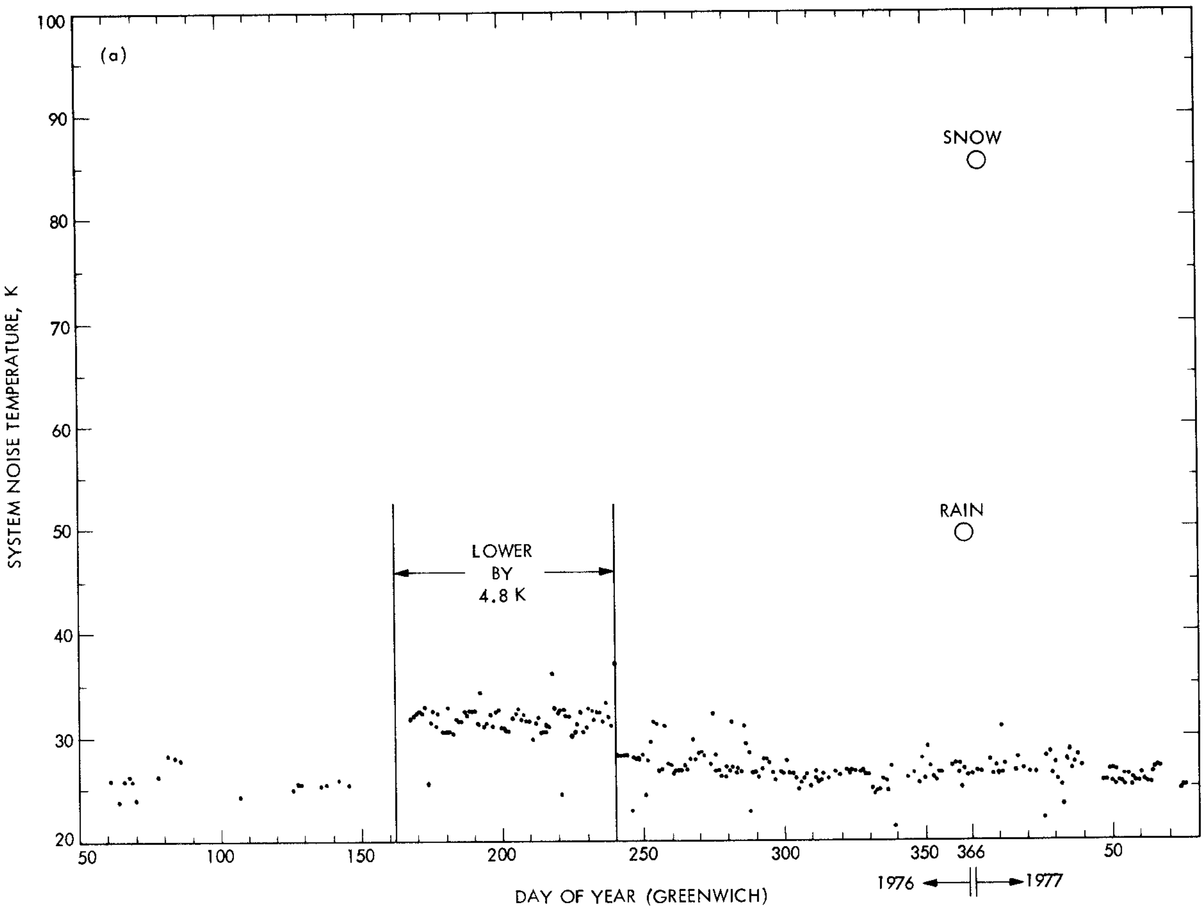


Fig. 1. Record of 76-77 SNT data: (a) Goldstone (DSS 14); (b) Canberra (DSS 43); (c) Madrid (DSS 63)

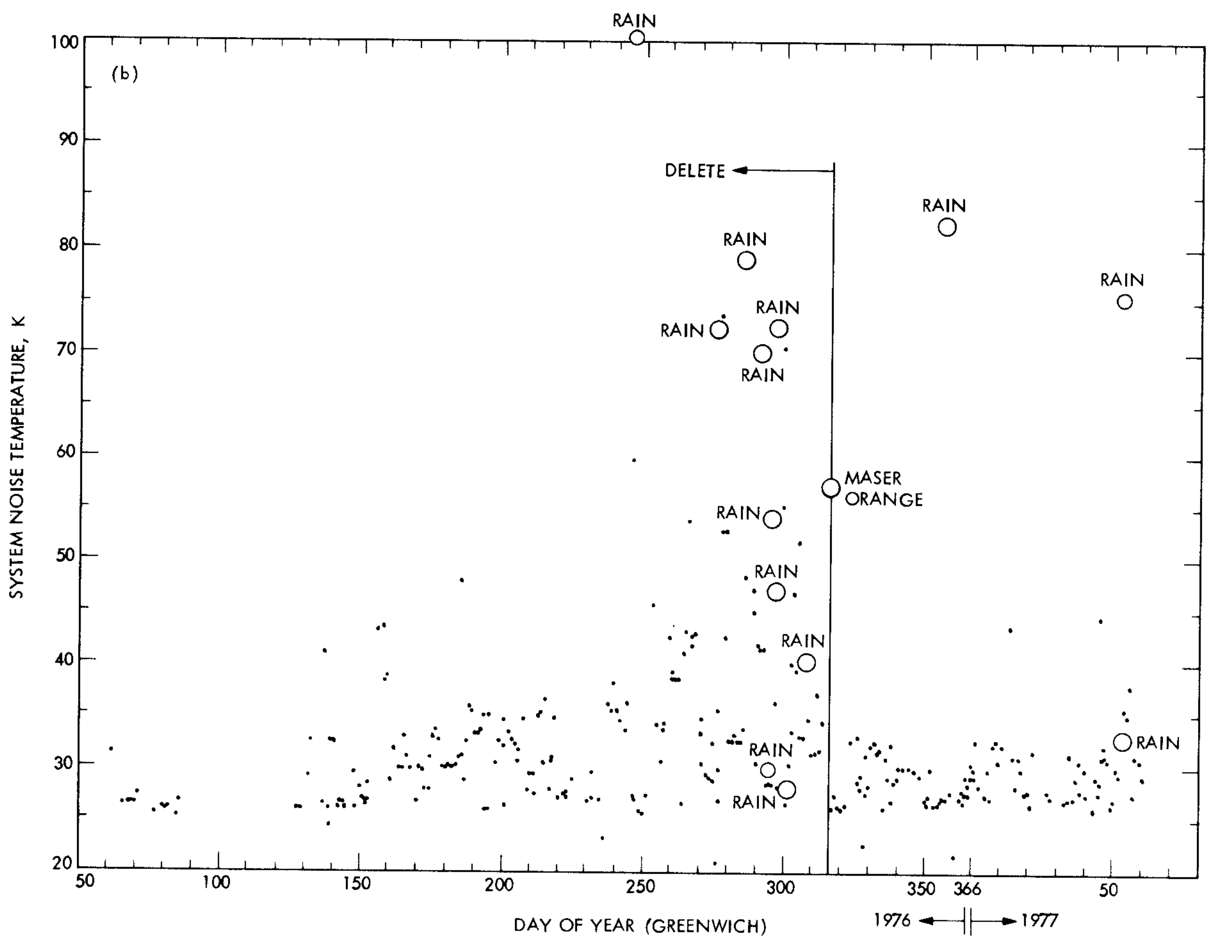
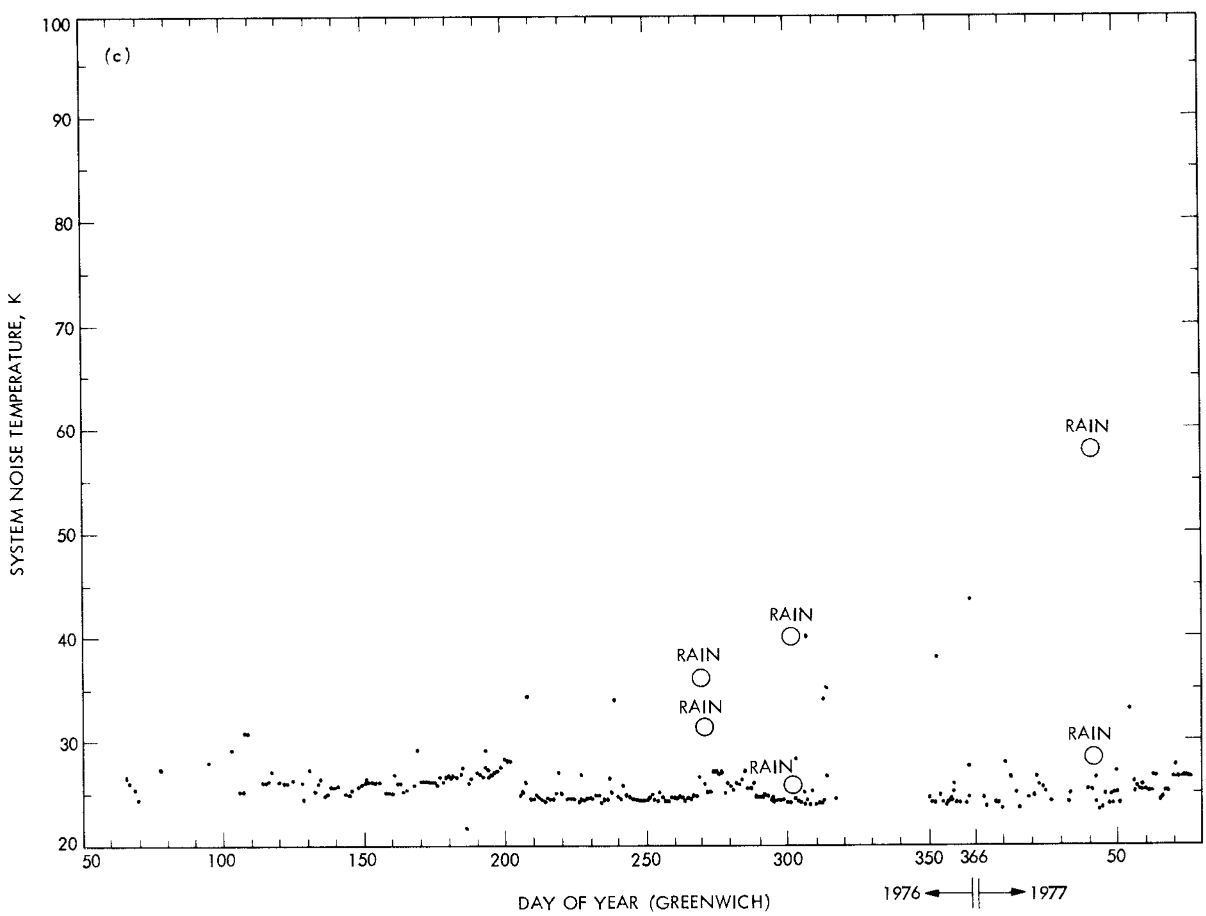

(b)
SYSTEM NOISE TEMPERATURE, K
DAY OF YEAR (GREENWICH)
1976
1977
DELETE
MASER ORANGE
RAIN
100
90
80
70
60
50
40
30
20
50
100
150
200
250
300
350
366
50

Fig. 1 (contd)



(c)
SYSTEM NOISE TEMPERATURE, K
100
90
80
70
60
50
40
30
20
RAIN
RAIN
RAIN
RAIN
RAIN
RAIN
50
100
150
200
250
300
350
366
50
DAY OF YEAR (GREENWICH)
1976
1977

Fig. 1 (contd)

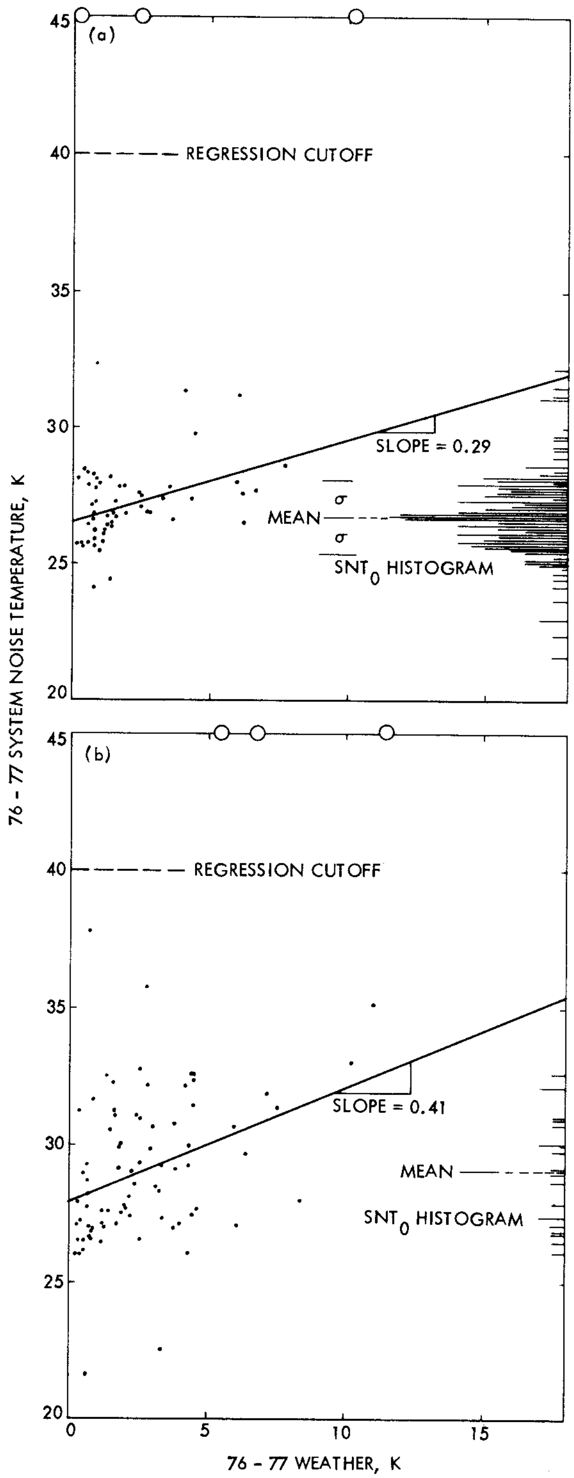


Fig. 2. Scatter plot of 76-77 SNT data vs 76-77 weather data, with histogram of SNT_0 data: (a) Goldstone; (b) Canberra; (c) Madrid

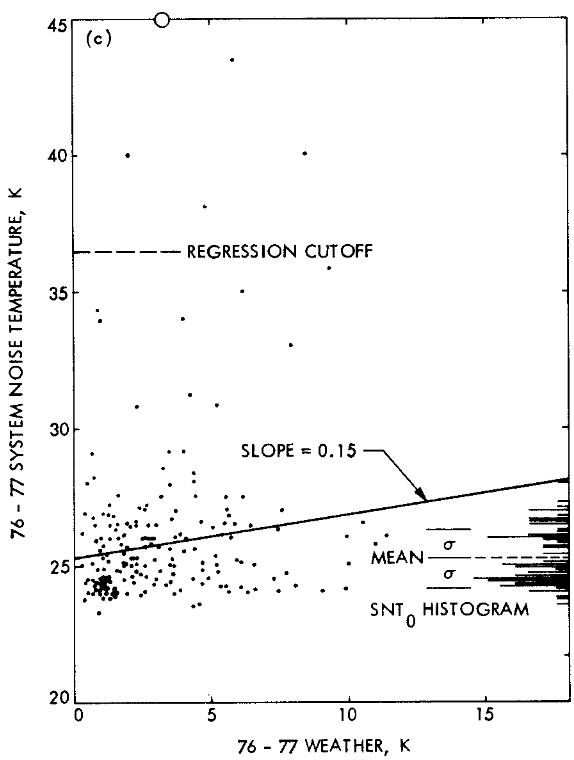

(c)
45
40
35
30
25
20
0
5
10
15
76 - 77 SYSTEM NOISE TEMPERATURE, K
76 - 77 WEATHER, K
REGRESSION CUTOFF
SLOPE = 0.15
MEAN
σ
σ
SNT$_0$ HISTOGRAM

Fig. 2 (contd)

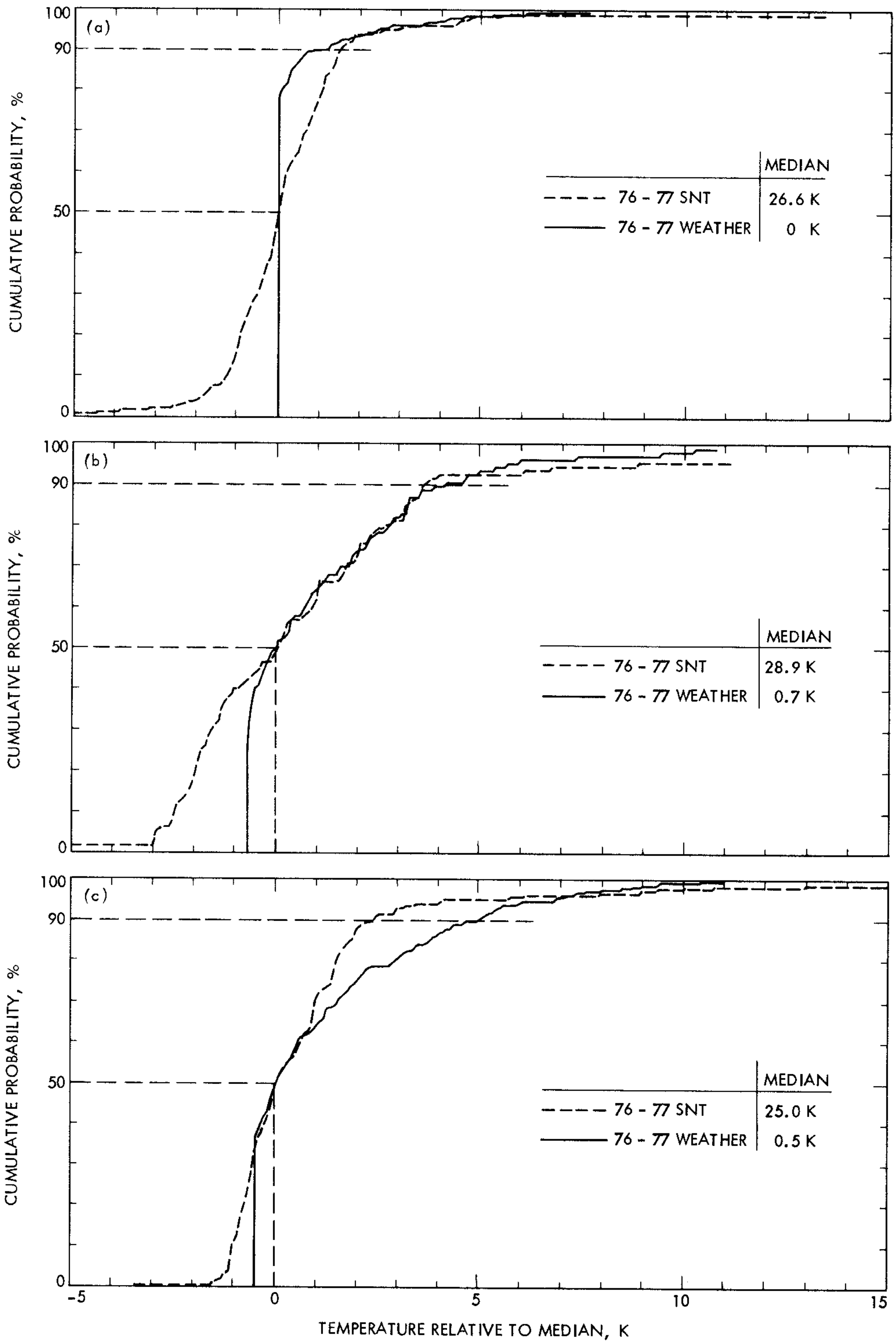


Fig. 3. Cumulative distribution functions of 76-77 SNT and weather data, tied at medians: (a) Goldstone; (b) Canberra; (c) Madrid

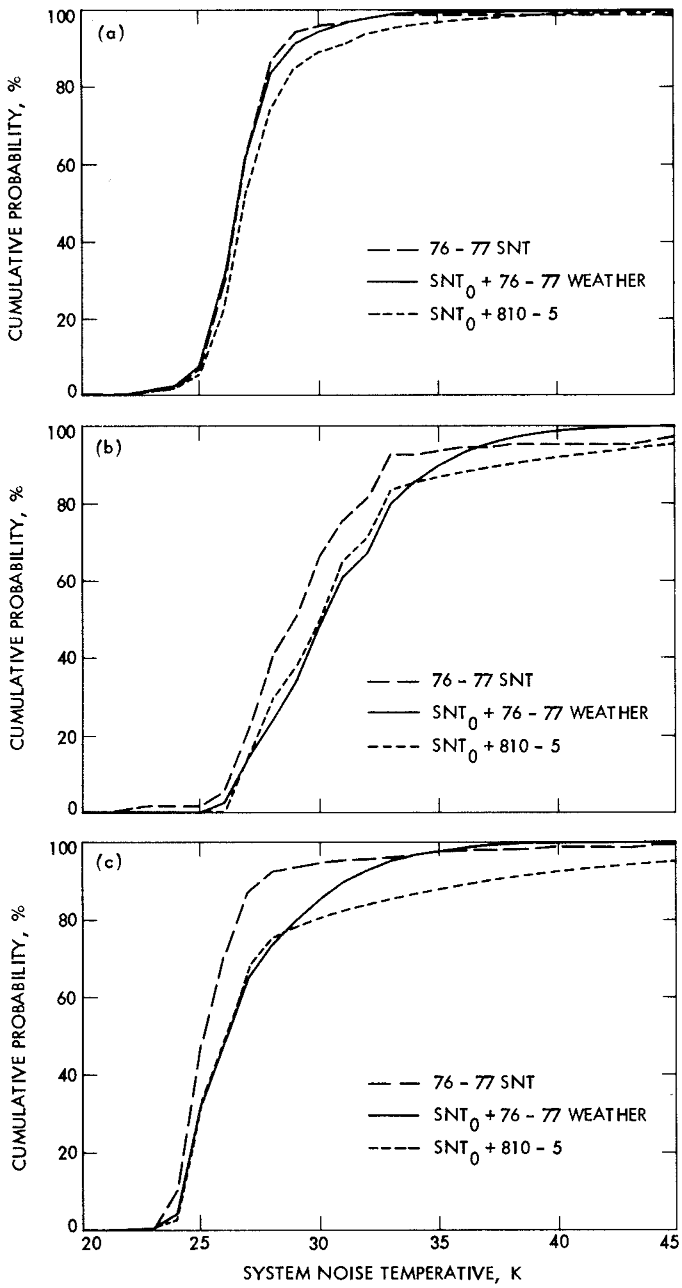


Fig. 4. Cumulative distribution functions of 76-77 SNT, SNT_0 + 76-77 weather, and SNT_0 + 810-5: (a) Goldstone; (b) Canberra; (c) Madrid

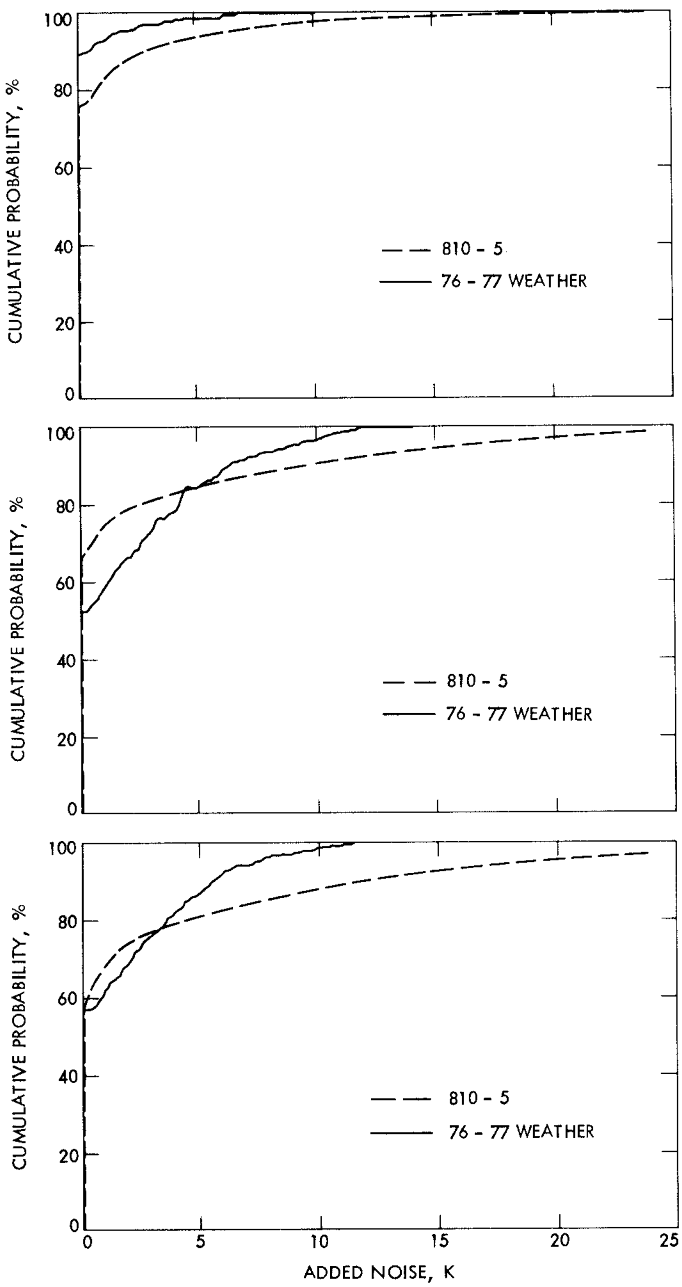


Fig. 5. Cumulative distribution functions of 76-77 weather and 810-5: (a) Goldstone; (b) Canberra; (c) Madrid